Contract/Grant Title: Operation and on-chip integration of cavity-QED-based detectors for single atoms and molecules

Contract/Grant #: FA9550-07-1-0046

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Final report

Abstract

A new experimental platform for studies of transport and quantum-limited measurements of cold, trapped atomic gases was constructed. Using microfabrication processes, a silicon wafer was micromachined to allow for deposition of micrometer-scale electromagnet wires and for the integration of closely spaced, highly reflective optical mirrors. With this device, nanokelvin-temperature atomic gases were produced and placed with nanometer precision within a high-finesse optical resonator. This device was applied to a novel research direction pioneered by this group: the construction of a cavity optomechanical system with ultracold atomic gases, with the goals of understanding how to conduct quantum-limited measurements of the motion of a macroscopic mechanical object and characterizing the new phenomena arising in such a hybrid optomechanical quantum system. Key results to date include the tuning between linear and quadratic optomechanical regimes, allowing one to measure either the displacement or the strain of a compressible cantilever; the first characterization of optomechanical effects in the quadratic coupling regime; and quantitative matching between experimental observations and simple theoretical predictions that establish the validity of this innovative use of cold atomic gases.

Research accomplishments:

Our efforts over the granting period were focused on three activities: construction of a microfabricated atom chip with high-finesse optical resonators to allow new studies and applications of quantum gases, using an existing apparatus to develop the idea of realizing cavity optomechanics with ultracold atoms serving as the mechanical element, and using the newly built chip-based apparatus to realize new regimes of optomechanics. We describe each of these in turn.

Atom chip construction and operation

Microfabricated atom chips allow for the construction of complex experiments using ultracold atoms that are trapped and manipulated off the surface of the chip. A major goal of the AFOSR grant was to develop such atom chips with the capacity for operating on-board high-finesse optical resonators that would be used to detect and manipulate the chip-trapped atoms. This goal was accomplished during the first year of the grant. Deep reactive ion etching (DRIE) was used on both surfaces of a silicon substrate to define deep channels for copper-wire electromagnets that were deposited thereafter through electroplating and chemical-mechanical polishing. DRIE was also used to reduce the thickness of the atom chip at two locations where high-quality mirrors were mounted just off the chip surfaces. These mirrors formed two Fabry-Perot resonators with mode volumes crossing the chip surface through an etched hole, and with sufficiently small mode volumes and high finesse to achieve the strong-coupling criterion of cavity quantum electrodynamics (dominant single-atom/single-photon coupling).

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14. ABSTRACT
A new experimental platform for studies of transport and quantum-limited measurements of cold, trapped atomic gases was constructed. Using microfabrication processes, a silicon wafer was micromachined to allow for deposition of micrometer-scale electromagnet wires and for the integration of closely spaced, highly reflective optical mirrors. With this device, nanokelvin-temperature atomic gases were produced and placed with nanometer precision within a high-finesse optical resonator, and to construct a cavity optomechanical system with ultracold atomic gases, with the goals of understanding how to conduct quantum-limited measurements of the motion of a macroscopic mechanical object and characterizing the new phenomena arising in such a hybrid optomechanical quantum system. Key results include the tuning between linear and quadratic optomechanical regimes, allowing one to measure either the displacement or the strain of a compressible cantilever; the first characterization of optomechanical effects in the quadratic coupling regime; and quantitative matching between experimental observations and simple theoretical predictions that establish the validity of this innovative use of cold atomic gases.

15. SUBJECT TERMS
Ultracold atomic gases, atom chips, quantum metrology, force sensors, cavity optomechanics

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This atom chip was mounted on a specialized vibration isolated holder within a new ultra-high vacuum chamber. Extensive infrastructure was developed to enable experiments using ultracold atoms trapped on the chip; such infrastructure includes arrays of externally controlled current sources, a laser-optical system for laser cooling atoms within the chamber, a sophisticated laser system for stabilizing and probing the on-chip optical resonator, imaging and data analysis systems, etc. During the second year of the grant period, these experimental subsystems were integrated to allow for cold atoms to be loaded onto the atom chip, transported from the loading region into the volume of the on-chip optical resonator, and delivered into an all-optical trap supported by the Fabry-Perot cavity. This atom-chip experiment is among the first to integrate successfully the technologies of ultracold atomic physics and cavity quantum electrodynamics.

Cavity optomechanics with ultracold atoms

During the construction of the atom chip apparatus, a second, existing apparatus was used to develop the notion of using cold atoms for studies of cavity optomechanics. Cavity optomechanical systems are being developed in laboratories around the world, on scales ranging from nanofabricated cantilevers and resonators to kilogram-scale mirrors and kilometers-long interferometers used to search for gravity waves (LIGO). In such systems, the goal of achieving ever-better sensitivity to the motion of a macroscopic mechanical object has necessitated the understanding and control of quantum effects that ensue from the cavity and mechanical object forming a coupled quantum system.

We pioneered the idea of using ultracold quantum gases as the mechanical object in a cavity optomechanical system. Under several regimes of atomic confinement, the collective, spatially dependent coupling between resonant cavity photons and an atomic ensemble isolates a single mechanical degree of freedom of the ensemble to which the cavity is sensitive and upon which the back-action forces of cavity photons act. The atomic ensemble thereby acts as a gas-phase analogue of the typically solid-phase cantilevers used in cavity optomechanics experiments. The gas-based approach has the advantages of entering immediately into the quantum regime of mechanical motion, owing to the extremely low temperatures of the atomic gases, of being described *ab initio* from simple theories of quantum optics and atomic physics, and of allowing for a newly identified "granular" strong-coupling regime of cavity optomechanics for which the theory is poorly developed [see ICAP Proceedings (2009) for details].

We obtained two important experimental results in developing this connection. First, we identified the collective atomic motion of an intracavity atomic ensemble as the source for nonlinear cavity optics. Remarkably, such nonlinearities were significant, e.g. in that driven cavities displayed optical bistability, even with the average intracavity photon number being far below unity (as low as 0.02). This unprecedented regime of nonlinear optics is achieved due to the strong collective optomechanical coupling, and the persistent motional coherence of an ultracold atomic gas [PRL **99**, 213601 (2007)]. Second, we performed the first quantification of the backaction from a quantum measurement of the position of a macroscopic object. This backaction effect was detected bolometrically: the backaction disturbance caused momentum-diffusion of the mechanical object, generating heat that was measured by the evaporation rate of atoms from the intracavity trap. The measured backaction heating rate was at a level matching quantum metrological limits [Nature Physics **5**, 561 (2008)].

Tunable cavity optomechanics on an atom chip

The atom-chip developed in this project offers distinct advantages to the study of cavity optomechanics with ultracold atoms. The third year of the granting period was devoted to exploiting these advantages. Specifically, the tight magnetic confinement provided by the atom chip wires allows atoms to be confined to micron length scales, and to be positioned precisely within the volume of a Fabry-Perot optical resonator. Transferring these magnetically positioned atoms into a standing-wave optical trap supported by the Fabry-Perot cavity itself, one may place the atomic ensemble selectively between the nodes and antinodes of the cavity probe field. The consequence of such precise control for optomechanics is the ability to tune the optomechanical coupling parameters. At the nodes and antinodes of the probe field, the coupling between the atomic ensemble and the cavity field is such that the cavity response to atomic displacement is quadratic at lowest order; in contrast, between these locations, the response is dominantly linear. We have recently demonstrated such tunability in both the strength and also the character of optomechanical coupling. Several optomechanical effects were characterized experimentally, including cavity optomechanical bistability and optomechanical frequency shifts (the "optical spring" effect), providing the first observations of such effects in the quadratic optomechanical regime [manuscript in preparation].

Doctoral student training:

The AFOSR grant supported the doctoral studies of four students, two of whom were awarded their Ph.D. degrees during the granting period. The first is Dr. Kater Murch. His dissertation, entitled "Cavity Quantum Optomechanics with Ultracold Atoms," explains how cavity optomechanics is realized with ultracold atomic ensembles and presents two major experimental products of that realization: strong nonlinear cavity optics due to collective atomic motion, and the first quantification of measurement backaction for a macroscopic object. Dr. Murch is pursuing postdoctoral research on mesoscopic superconducting circuitry and quantum measurement with Prof. Irfan Siddiqi at UC Berkeley.

The second student graduating with the support of the AFOSR is Dr. Thomas Purdy. His dissertation, entitled "Cavity QED with Ultracold Atoms on an Atom Chip," documents the successful construction of microfabricated atom chips of two varieties: a silicon-substrate chip with on-chip microfabricated mirrors and high-speed thermal actuation of a high-finesse optical resonator, and the silicon-substrate chip described above. Novel capacities for the study of cavity optomechanics are realized by placing atomic ensembles selectively within one (or maybe three) wells of an optical lattice potential, and the first optomechanics experiments on such ensembles are presented. Dr. Purdy has received an NRC Postdoctoral Fellowship to conduct research with Profs. Cindy Regal and Jun Ye at NIST Boulder.

Archival publications during granting period:

- Gupta, S., K. L. Moore, K. W. Murch and D. M. Stamper-Kurn. "Cavity nonlinear optics at low photon numbers from collective atomic motion." <u>Physical Review Letters</u> **99**, 213601, (2007)
- Purdy, T. P. and D. M. Stamper-Kurn. "Integrating cavity quantum electrodynamics and ultracold-atom chips with on-chip dielectric mirrors and temperature stabilization." <u>Applied Physics B-Lasers and Optics</u> **90**, 401 (2008).
- Murch, K. W., K. L. Moore, S. Gupta and D. M. Stamper-Kurn. "Observation of quantum-measurement backaction with an ultracold atomic gas." <u>Nature Physics</u> **4**, 561 (2008).

- Botter, T., D. Brooks, S. Gupta, Z.-Y. Ma, K. L. Moore, K. W. Murch, T. P. Purdy and D. M. Stamper-Kurn (2009). “Quantum micro-mechanics with ultracold atoms.” Proceedings of the XXI International Conference on Atomic Physics. R. Cote, P. Gould, M. Rozman and W. W. Smith, World Scientific: 117 - 130.

Change in research objectives, if any:

During this granting period, our research focus has veered slightly from performing quantum measurements of single chip-trapped atoms to performing such measurements on collective properties of atomic ensembles.

Change in AFOSR program manager:

The grant was managed initially by Dr. Anne Matsuura and later by Dr. Tatjana Curcic, both within the Atomic and Molecular Physics program of the Physics and Electronics directorate.

Extensions granted or milestones slipped, if any:

None

New discoveries, inventions, patent disclosures:

None